Floc Dynamics and Facies Generation on the Margins of the Adriatic Sea

Paul S. Hill
Department of Oceanography
Dalhousie University
Halifax, Nova Scotia, CANADA B3H 4J1
Phone: (902) 494-2266 fax: (902) 494-3877 email: paul.hill@dal.ca

Timothy G. Milligan
Fisheries and Oceans Canada
Bedford Institute of Oceanography
1 Challenger Drive
Dartmouth, Nova Scotia, CANADA B2Y 4A2
Phone: (902) 426-3273 fax: (902) 426-6695 email: milligant@mar.dfo-mpo.gc.ca

Award Number: N00014-97-1-0160, N00014-99-0113

LONG-TERM GOALS

The goal of this research is to develop greater understanding of the dynamics of fine-grained sediment and its role in the generation of sedimentary facies on the continental shelf. In particular, we seek greater understanding of the environmental processes that influence the degree of packaging of fine-grained sediment within flocs (floc fraction), and the role of boundary shear stress in determining the change in sediment size and sorting that makes the sand-mud transition recognizable acoustically as well as lithologically.

SCIENTIFIC OBJECTIVES

This research has three objectives:

1. To determine the role of floc fraction in the removal of sediment from riverine discharge plumes;
2. To determine the controls on floc fraction in the bottom nepheloid layer;
3. To determine the role of floc fraction in the formation of the sand-mud transition.

APPROACH

We pursue two basic approaches to quantifying floc fraction. The first requires co-located measurements of in situ floc size and volume concentration and total suspended particulate mass (SPM) concentration. It also requires an in situ floc size versus settling velocity relationship, which is used to convert floc volume concentration to floc mass concentration. Floc fraction is derived by dividing floc mass concentration by total SPM concentration (e.g., Curran et al., 2002a). The second method applies an inverse model of sedimentation to disaggregated inorganic grain size (DIGS) distributions in the seabed to estimate the grain size for which flux to the seabed within flocs equals the single-grain flux. Paired with an estimate of mean floc settling velocity, this diameter, termed the "floc limit", can be used to calculate floc fraction in suspension (Curran et al., accepted). Our recent

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2003**	2. REPORT TYPE	3. DATES COVERED **00-00-2003 to 00-00-2003**

4. TITLE AND SUBTITLE **Floc Dynamics and Facies Generation on the Margins of the Adriatic Sea**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Dalhousie University,,Department of Oceanography,,Halifax, Nova Scotia, CANADA B3H 4J1,, ,**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The goal of this research is to develop greater understanding of the dynamics of fine-grained sediment and its role in the generation of sedimentary facies on the continental shelf. In particular, we seek greater understanding of the environmental processes that influence the degree of packaging of fine-grained sediment within flocs (floc fraction), and the role of boundary shear stress in determining the change in sediment size and sorting that makes the sand-mud transition recognizable acoustically as well as lithologically.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

work in the Po delta demonstrates remarkably good agreement between these methods (Fox et al., accepted).

A new instrument called INSSECT, which stands for **IN** situ **S**ize and **SE**ttling **C**olumn **T**ripod, was designed to determine the size and settling velocity of suspended material in situ, as well as capture flocs. The package includes a digital floc camera to observe the ambient floc population (Milligan, 1996, Milligan and Hill, 1998), a digital video camera to measure the size and settling velocity in the settling column, and a timed sediment trap consisting of 24 programmable cups containing polyacrylamide gel to collect flocs intact. Also mounted on the INSSECT are a LISST, OBS, MAVS acoustic current meter, and a compass/tilt package. INSSECT was deployed on the Po prodelta and on the Apennine Margin in February and May 2003. Results from this instrument are being used to determine the size-settling velocity relationship for flocs in the Western Adriatic and testing the validity of Stokes Law for permeable aggregates.

All work is being conducted collaboratively between Tim Milligan of Bedford Institute of Oceanography (BIO) and Paul Hill of Dalhousie University. Milligan takes primary responsibility for equipment design, data acquisition, and particle size analysis. Hill takes primary responsibility for modelling, data analysis, and communication of results. Danish post-doctoral fellow Ole Mikkelsen has taken primary responsibility for deployment of INSSECT. Jason Fox and Doug George (Dalhousie) are two graduate students funded by this project, and Brent Law (BIO) has provided technical support in the laboratory and field.

WORK COMPLETED

Our EuroSTRATAFORM fieldwork in the Adriatic is complete, and currently we are engaged in data analysis and publication of results. Our work in the Adriatic comprised four sub-projects:

1. Documentation of particle packaging in the Po River plume;
2. Interpretation of the temporal evolution of seabed DIGS on the Po prodelta;
3. Characterization of the spatial and temporal variability of floc properties in the bottom boundary layer of the western Adriatic;
4. Mapping and dynamic interpretation of the position of the sand-mud transition on the Apennine margin.

An examination of in situ fine-grained sediment packaging and its effect on sediment transport on the Po prodelta has been completed, and the results have been accepted or submitted for publication (Fox et al., accepted; Fox et al., submitted). Fox completed his MSc thesis on this work in spring 2003.

Analysis of the evolution of the DIGS of surficial sediment since the October 2000 flood of the Po River has been completed. Results were presented at the joint EGU/AGU conference in Nice, July 2003. Integration of these results with those of European colleagues is being carried out to examine the effect of floc fraction on the distribution of carbon on the Po prodelta.

To characterize floc properties in the bottom boundary layer, the INSSECT was deployed on the Po prodelta and near the mouths of the Chienti and Pescara Rivers on the Apennine margin in February and May 2003. The INSSECT gathered data on floc size versus settling velocity, in situ particle size as measured by our digital floc camera (DFC) and by a LISST-100, and current velocity and Reynolds stress during its two-day deployments. The rotating carousel of sediment-collecting cups was prone to

contamination by horizontal advection of sediment into the cups, so the data cannot be used to constrain mass flux.

Surficial sediment samples collected off of the Tronto and Pescara Rivers have been analyzed for DIGS, sediment specific surface area, clay mineralogy, carbonate content, and metals concentrations. Data interpretation has been completed and the results are contained in a working draft of an MSc thesis prepared by D. George at Dalhousie University. He is scheduled to defend his thesis in winter 2003-04.

RESULTS

Investigation of particle packaging in the Po revealed that sediment is extensively flocculated, that flocs are pre-formed in the river, and that the flocculation causes rapid, proximal loss of sediment from the Po plume (Fox et al., accepted). Comparison of suspension-based and sediment-based estimates of floc fraction found good agreement (Fox et al., submitted).

DIGS distributions have been measured at fixed depths within cores collected from 11 sites that were occupied in December 2000, June 2001, October 2001, November 2002, February 2003, and June 2003. These distributions indicate that flocculation played a bigger role in the deposition of surficial sediments on the prodelta immediately after the October 2000 flood than during later periods. This finding is consistent with the hypothesized positive correlation between sediment concentration and floc fraction that we proposed in our previous ONR-funded work (Curran et al., 2002b).

Preliminary results form the INSSECT demonstrate that size versus settling velocity relationships do not vary geographically or seasonally in the Adriatic and that they resemble relationships gathered in a variety of other environments. Comparison of LISST and DFC size distributions in their region of overlap indicates good agreement, opening the possibility of establishing full particle size distributions from micrometer to millimeter diameters. Establishing full in situ size distributions is vital for improvement of predictions of models of optical and acoustical properties of the water column.

Size-settling velocity data from the INSSECT video system documents the co-existence of two distinct floc populations in the water off the Po River in late May (Fig. 1). It is noteworthy that the two populations are settling at almost the same speed (0.5-2 mm/s), in spite of the large difference in size, suggesting the importance of floc structure and composition in determining settling speed. Conceivably, the floc populations are mainly inorganic (<560μm) and organic (>560 μm). Co-existing floc populations have been observed before in the field (e.g. Milligan et al., 2001), and in the laboratory (Milligan, 1995; Curran et al., 2003) but it has usually been assumed that flocs belonging to different populations would settle according to the same power law. This appears not to be the case.

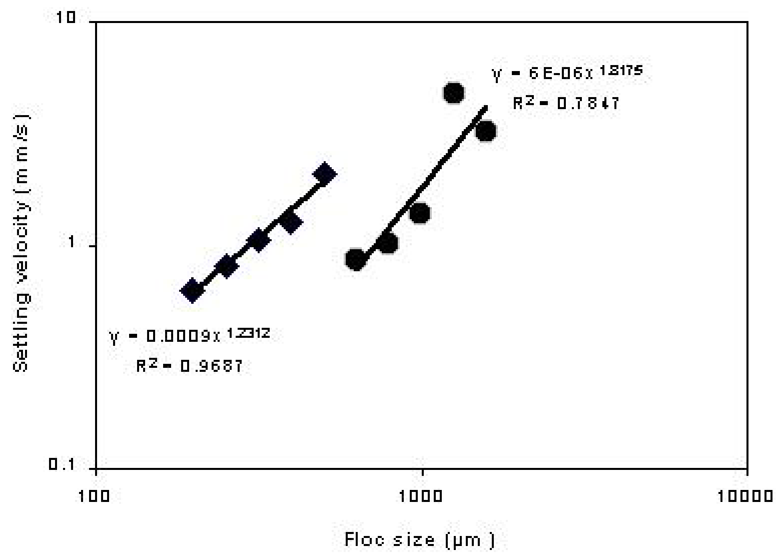

Figure 1: Graph showing the size - settling velocity relationship for flocs observed off the Po River, May 24-25, 2003. Two different relationships were observed suggesting that composition is a critical factor controlling floc size. Both relationships are power laws. In the first, floc diameter varies from200-800 micrometers, and settling velocity varies from 0.6 to 3.4 mm s^{-1}. The exponent relating settling velocity to diameter in the power-law relationship is 1.23. In the second, floc diameter varies from 800-2000 micrometers, and settling velocity varies from 1 to 5.2 mm s-1. The exponent of the power-law relationship is 1.82.

The video analysis also revealed that during a prolonged period of calm weather, fast settling flocs (~ 0.8 mm/s) settle out on a time-scale of days to weeks, leaving behind a "stranded" population of slow settling flocs (~ 0.3mm s^{-1}). The video data also reveals that floc settling velocities may vary up to two orders of magnitude within time scales of a few days.

Analysis of silhouette images of the ambient floc population obtained from the DFC shows floc break-up during a small storm event off of the Chienti River in May 2003 (Fig. 2). The data reveal that as a result of break-up both floc size and shape change. During the storm event, floc shape tends not to vary, with axis ratios ~ 1.5. After the storm, floc size increases rapidly and shape becomes more irregular as a result of the formation of large flocs.

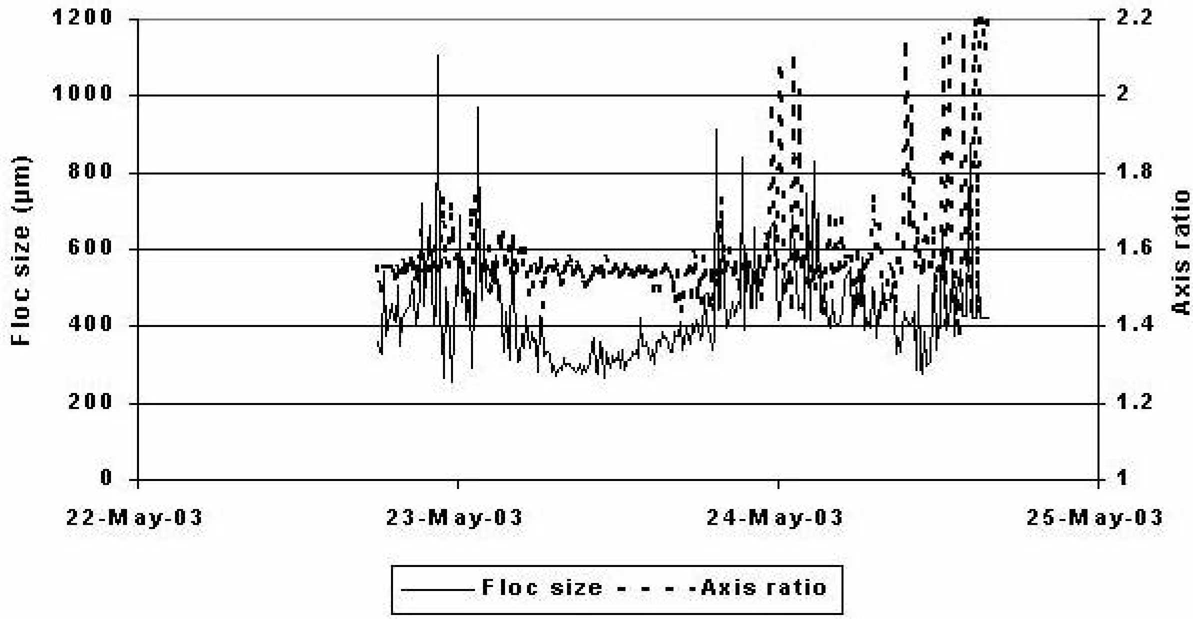

Figure 2: Results of image analysis of silhouette images taken off the mouth of the Chienti River, May 22-24, 2003. Median floc size (solid line) decreases from 600 micrometers at midnight on 23 May to approximately 300 micrometers by noon of the same day. This diameter decrease coincides with an increase in winds and waves at the site. By early morning on 24 May, as winds subsided, floc size returned to pre-event values. Mean floc major-to-minor axis ratios (dotted line) remained steady at 1.5-1.6 before, during, and after the wind event, but variability was reduced during the event. These results are interpreted to reflect floc breakup during the wind event, followed by floc reformation after the event.

Mapping and interpretation of the dynamic controls on the depth of the sand-mud transition on the Apennine margin has been carried out using analysis of DIGS, sediment specific surface area, clay mineralogy, carbonate content, and metals concentrations in surficial sediment on the Pescara and Tronto shelves. This work confirms that the sand-mud transition marks an abrupt change in the flux of flocculated material to the seabed and that this change affects geochemical properties of the seabed. Dimensional analysis has been carried out using the depths of other sand-mud transitions reported in the literature. Results of this analysis suggest that except in the case of extremely high sediment concentrations, the depth of the sand mud transition is controlled by significant wave height.

IMPACT/APPLICATION

Observations are helping to refine understanding of modes of delivery of fine-grained sediment from rivers and its incorporation into the sedimentary record. These observations suggest that the sand-mud transition, characterized by an abrupt change in sediment size and sorting, is the result of bottom stresses that scale with significant wave height. With the exception of shelves dominated by rivers with very high fine-grained sediment loads that overwhelm resuspension by wave stresses, these finding appear to be universal. Characterization of the entire particle size distribution and of floc fraction in suspension will lead to improved models of sediment transport and of the optical and acoustical properties of the water column.

TRANSITIONS

No Transitions

PATENTS

None

AWARDS

None

RELATED PROJECTS

The proposed parameterization of aggregation and disaggregation is being applied successfully to the interpretation of optical measurements gathered at the Coastal Mixing and Optics site by Oregon State University researchers. Collaborator is Emmanuel Boss (U.Maine)

Floc size versus settling velocity relationships and their dependence on fluid stress are being investigated with support from the Natural Sciences and Engineering Research Council in Canada, and as part of investigations into the fate and effects of drilling wastes on the continental shelf funded by the Panel on Energy Research and Development (Canada).

REFERENCES

Curran, K. J., P. S. Hill, T. M. Schell, T. G. Milligan, and D. J. W. Piper. Accepted. Inferring the mass fraction of floc-deposited mud: Application to fine-grained turbidites. *Sedimentology*.

Curran, K.J., P. S. Hill, and T. G. and Milligan. 2003. Time variation of floc properties in a settling column. *Journal of Sea Research*, 49: 1-9.

Curran, K.J., P.S. Hill and T.G. Milligan, 2002a. Fine-grained suspended sediment dynamics in the Eel River flood plume. *Continental Shelf Research*, 22: 2537-2550.

Curran, K.J., Hill, P.S., and Milligan, T.G. 2002b. The role of particle aggregation in size-dependent deposition of drill mud. *Continental Shelf Research*. 22(3):403-414.

Fox, J. M., P. S. Hill, T. G. Milligan, and A. Boldrin. Accepted. Flocculation and sedimentation on the Po River delta. *Marine Geology*.

Fox, J. M., P. S. Hill, T. G. Milligan, A. S. Ogston, and A. Boldrin. Submitted. Floc fraction in the waters of the Po River prodelta. *Continental Shelf Research*.

Milligan, T.G., 1995, An examination of the settling behaviour of a flocculated suspension, *Neth. Journal of Sea Research*., 33(2), 163-171.

Milligan, T.G., 1996, In-situ particle (floc) size measurements with the Benthos 373 plankton silhouette camera. *Journal of Sea Research*, **36**: 93-100.

Milligan, T.G. and P.S. Hill, 1998. A laboratory assessment of the relative importance of turbulence, particle composition, and concentration in limiting maximal floc size and settling behaviour, *Journal of Sea Research*. 39/3-4, 227-241.

Milligan, T.G., G. C. Kineke, A. C. Blake, C. R. Alexander, and P. S. Hill. 2001. Flocculation and Sedimentation in the ACE Basin, South Carolina. *Estuaries* 24: 734-744.

PUBLICATIONS

Curran, K. J., P. S. Hill, and T. G. Milligan. 2003. Time variation of floc properties in a settling column. *Journal of Sea Research,* **49:** 1-9. [published, refereed]

Curran, K. J., P. S. Hill, and T. G. Milligan. 2002. Fine-grained suspended sediment dynamics in the Eel River flood plume. *Continental Shelf Research,* **22:** 2537-2550. [published, refereed]

Fox, J. M., P. S. Hill, T. G. Milligan, and A. Boldrin. 2003. Flocculation and sedimentation on the Po River delta. *Marine Geology*. [in press, refereed]

Fox, J. M., P. S. Hill, T. G. Milligan, A. S. Ogston, and A. Boldrin. 2003. Floc fraction in the waters of the Po River prodelta. *Continental Shelf Research*. [submitted, refereed]